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ABSTRACT

This study aimed to identify the main difficulties faced by physics students and then devise teaching units to overcome the difficulties, and to investigate whether there was any improvement in achievement in physics if mathematical skills were being stressed explicitly in physics lessons. The topics chosen for this study were graphs, errors, and vectors. Three different sets of pre- and post-tests were designed to accomplish the purposes of study. The aim of the pre-tests was to determine the weaknesses of the students in mathematical skills and transfer skills, from which three teaching units were especially designed for the experimental group. The fused curriculum was adopted to integrate the two subject areas and the combination of interrogatory, demonstration and prototype development instructional methods was implemented with emphasis on immediate feedback and corrective teaching. Student achievement from both control and experimental groups were measured by the post-tests. Analysis of treatment effects supported the notion that with adequate emphasis on mathematical skills and fostering transfer skills in the physics tutorial lessons, students' performance in solving physics problems could be significantly improved. Pre- and post-test items are listed in the appendices. (Author/YP)

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THE EFFECTS OF INCORPORATING MATHEMATICS TO PHYSICS INSTRUCTION ON PHYSICS LEARNING

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Abstract

This study was undertaken in view of the fact that many pre-university students had difficulties with mathematical skills as well as transfer of mathematical skills in solving physics problems. The study aimed: (a) to identify the main difficulties faced by the students and then devise teaching units to overcome the difficulties; (b) to investigate whether there was any improvement in achievement in physics if mathematical skills were being stressed explicitly in physics lessons. The topics chosen for this study were: Graphs, Errors and Vectors. Three different sets of pre- and post-tests were designed to accomplish the purposes of study. The aim of the pre-tests was to determine the weaknesses of the students in mathematical skills and transfer skills, from which three teaching units were specially designed for the experimental group. The fused curriculum was adopted to integrate the two subject areas and the combination of interrogatory, demonstration and prototype development instructional methods was implemented with emphasis on immediate feedback and corrective teaching. Students' achievements from both control and experimental groups were measured by the post tests. Analysis of treatment effects strongly supported the notion that with adequate emphasis on mathematical skills and fostering transfer skills in the physics tutorial lessons, students' performance in solving physics problems could be significantly improved.

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1. INTRODUCTION

It has been reported that many students cannot estimate, cannot calculate with approximate numbers, cannot read graphs and do not know how and when to make approximations when being encountered with Physics problems. The difficulties surface more at the junior college level where such skills are integral part of the Physics course. Students should use concepts in Mathematics as tools to tackle situations met in Physics.

At the 'A' level stage, several projects have been carried out. One such undertaking is the Sixth Form Mathematics Project which has produced packages on Indices, Quadratic Model and Limits. Another very useful work has been due to the Joint Royal Society/Institute of Physics Education Committee in compiling a list of the "Mathematical Needs of A-level Physics Students". Many findings have also indicated that achievement in Science is dependent on Mathematics knowledge and the ability to perform mathematical operations.

2. PURPOSE OF STUDY

This study aims to investigate the main difficulties with Mathematics knowledge in solving Physics problems and then devise teaching units to overcome these difficulties, if any. The areas of Physics chosen are Graphs, Errors, Composition of Vectors and Resolution of a Vector. The main task is to link Physics and Mathematics and use Mathematics as a tool to solve Physics problems. In so doing, it is hoped that the major difficulties encountered by students can be highlighted and then lessons could be planned accordingly.

The questions to be answered in this study are:

(a) What are the major difficulties, as far as Mathematics skills are concerned, that students face when solving Physics problems?

(b) Is there any difference in students' achievement in Physics when Mathematics skills are being stressed in Physics tutorial lessons?

3. DESIGN OF STUDY

3.1 Sample

The experimental group consisted of a total of

33 students. The subject combination of this group was Physics, Chemistry, Mathematics B and Economics.

The control group, comprised 37 students. The subject combination was Physics, Chemistry/Computer Science, Mathematics B and Further Mathematics.

Although the students were under the charge of different tutors, they were taken by the same lecturers. Also, the control group seemed to be a better class in terms of achievement by the fact that they were in a double mathematics class.

3.2 Description of Instrument

There were a total of three sets of tests, the first being a pre-test and post-test on Graphs the second on Errors, and the third on Vector Resolution and Composition of Vectors. The aim of the pre-tests is to determine the weaknesses of the students in mathematics from which the lessons will be geared to combat these weaknesses, if any.

The pre-tests were administered to both groups. These tests were used to test if there is any significant difference in the two groups as well as to determine the weaknesses of the students in mathematical skills and transfer skills in solving physics problems.

3.2.1 The Pre-Test

Graphs

The pre-test consisted of six questions in which students were asked to transform the given equations into straight-line form, stating the horizontal and vertical axes, gradient and intercept. The six questions attempted to cover as many aspects of straight-line graphs as possible. This pre-test aimed to determine the Mathematics knowledge especially the

manipulation skills that students had gained from their Secondary Four Mathematics course.

Errors

The pre-test comprised two main questions. The first question was to write down the maximum error or fractional error of the given expressions. The second question tried to link to the corresponding parts in question one under some given Physics situations. The error in addition, subtraction, product and ratio of two variables was to be calculated. The test also could gauge how students managed with significant figures. The main purpose of this test was to find out students' mathematics knowledge in differentiation and ratio/fraction as well as ability in transfering mathematical skills to physics problems.

Composition of Vectors and Resolution of a Vector

The test was designed to find out students' mathematical knowledge that were required for the topics in Mechanics. Questions were set to test students' knowledge in trigonometry and their understanding of the concepts of vectors. Questions were also set to find out students' ability in applying concepts of vector in solving simple physics problems.

3.2.2 The Post-Tests

The post-tests were designed as evaluative tests which were used to measure students' performances after the teaching units had been implemented to them.

Graphs

The post-test consisted of two questions. The first part of each question required students to transform

a given equation into a straight line form, similar to that in the pre-test, which was to be used to find certain quantities based on Physics knowledge in the second part.

The test were planned to assess the proficiency of the skills such as manipulation, transfer, interpretation, presenting skills as well as the application of these skills in solving physics problems.

Errors

This post-test consisted of three questions on application of simple error analysis to Physics problems involving addition, product as well as indices (power) of two or more variables. The questions were pitched at a higher level than those in the pre-test.

The skills to be tested were given in the table below:

Question	Skills
Part (a) of each question	° Manipulation skills in differentiation ° Making approximation
Part (b) of each question	Skills involved in solving physics problem: ° Transfer ° Making approximation ° Interpretation ° Presentation

Composition of Vectors and Resolution of a Vector

This post-test consisted of questions covering the topics of vector addition, Vector subtraction and Vector resolution. The questions were designed to test whether students were able to apply the knowledge of vector they had

learnt in the tutorial lessons to solve more complicated physics problems related to resolution of force/acceleration, resultant force/velocity, relative velocity and forces in equalibrium.

3.3 Conceptual Framework

The study attempted to make use of the remedy instruction, that emphasized on remedying deficient mathematical skills and fostering transfer of mathematical skills, to improve students' achievement in physics. The conceptual framework of this treatment process is shown in Figure 1.

The treatment consisted of two sections:

(a) Treatment Phase 1

- Identifying students' deficiency in mathematical skills and transfer of skills as a tool in solving physics problem.
- Remedying deficient mathematical skills in Physics tutorial lessons.
- Emphasizing interface between physics and mathematics by using various examples.

(b) Treatment Phase 2

- Highlighting the process of logical thinking and reasoning in analysing physics problems.
- Illustrating the application of physics concepts and the transfer of mathematical skills in solving physics problems.
- Encouraging students to be involved in solving physics problems.
- Implementing on-going and continual monitoring.

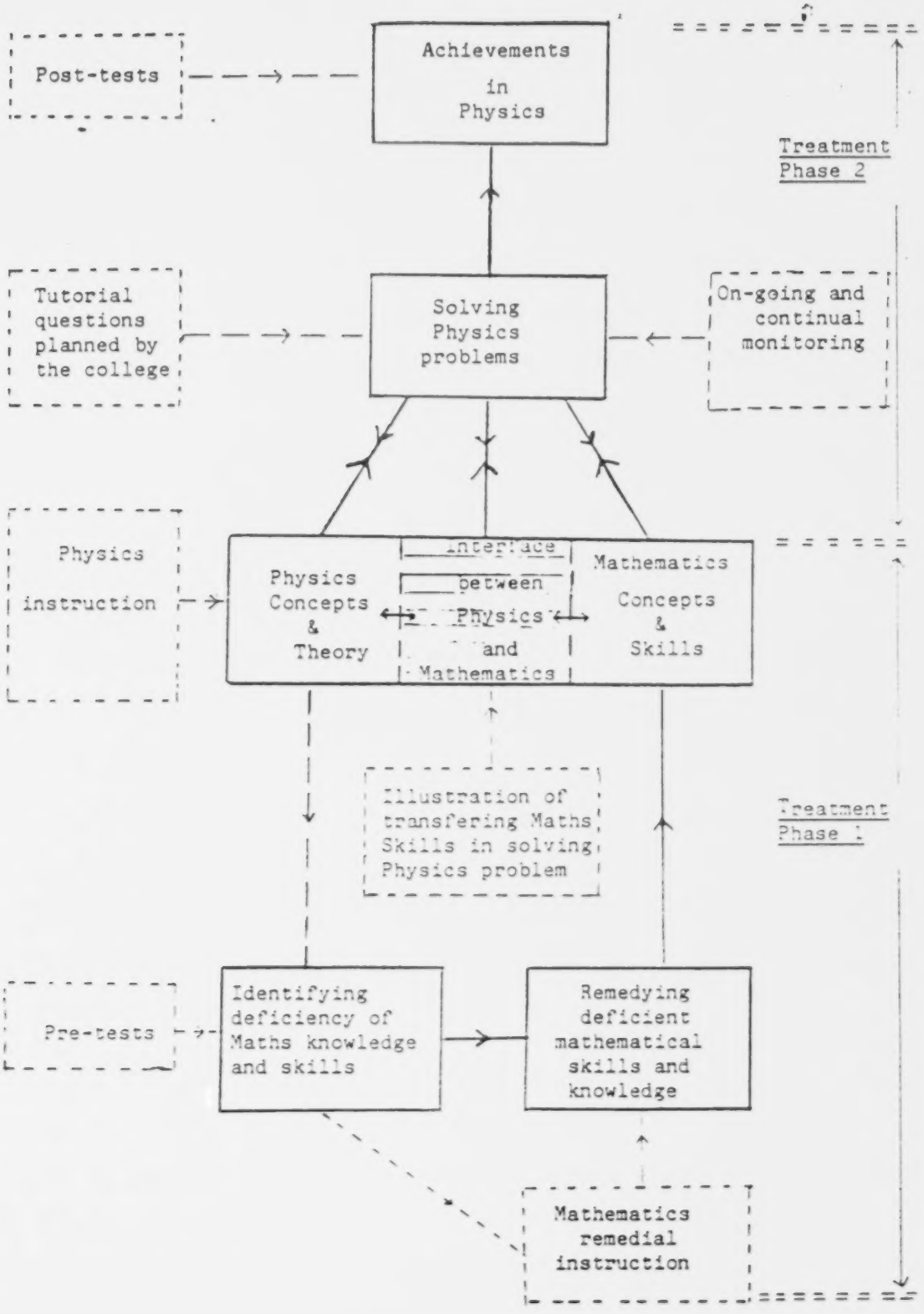
Post-tests
Achievements in Physics
Treatment Phase 2
Tutorial questions planned by the college
Solving Physics problems
On-going and continual monitoring
Physics instruction
Physics Concepts & Theory
Interface between Physics and Mathematics
Mathematics Concepts & Skills
Illustration of transfering Maths Skills in solving Physics problem
Treatment Phase 1
Pre-tests
Identifying deficiency of Maths knowledge and skills
Remedying deficient mathematical skills and knowledge
Mathematics remedial instruction

Figure 1. Conceptual Framework

3.4 Teaching Units

After each pre-test, the weaknesses of the students with regards to mathematics knowledge and transfer of skills in solving physics problems were carefully diagnosed. Based on the analysed results, three teaching units were specially designed for the students in the experimental group.

Graphs

Graphs construction and interpretation are important skills to both physics and mathematics education. However many students have not aquired these valuable skills especially the skills in graph interpretation. The important role of graphs in learning physics, coupled with deficiencies in graphing abilities suggests that melioration in instruction should be made to overcome the problems. We should ensure that the teaching unit we plan is able to assist students to achieve the following objectives.

(a) The content of the objectives in the area of mathematics includes:
- selecting appropriate axes
- locating points on a graph
- drawing lines of best fit
- interpolating, extrapolating
- describing relationships between variables
- interrelating the data
- transforming complicate equations into simple straight line equation

(b) The content of the objectives in the area of physics includes:
- selecting appropriate axes and assigning the corresponding physical quantities
- calculating of gradient with correct unit
- interpreting the dependent physical quantity correctly from the gradient of the graph
- presenting the result with appropriate significant figures and unit

The outlines of the content of the teaching unit as well as the procedure in presenting the unit are summarized in Figure 2.

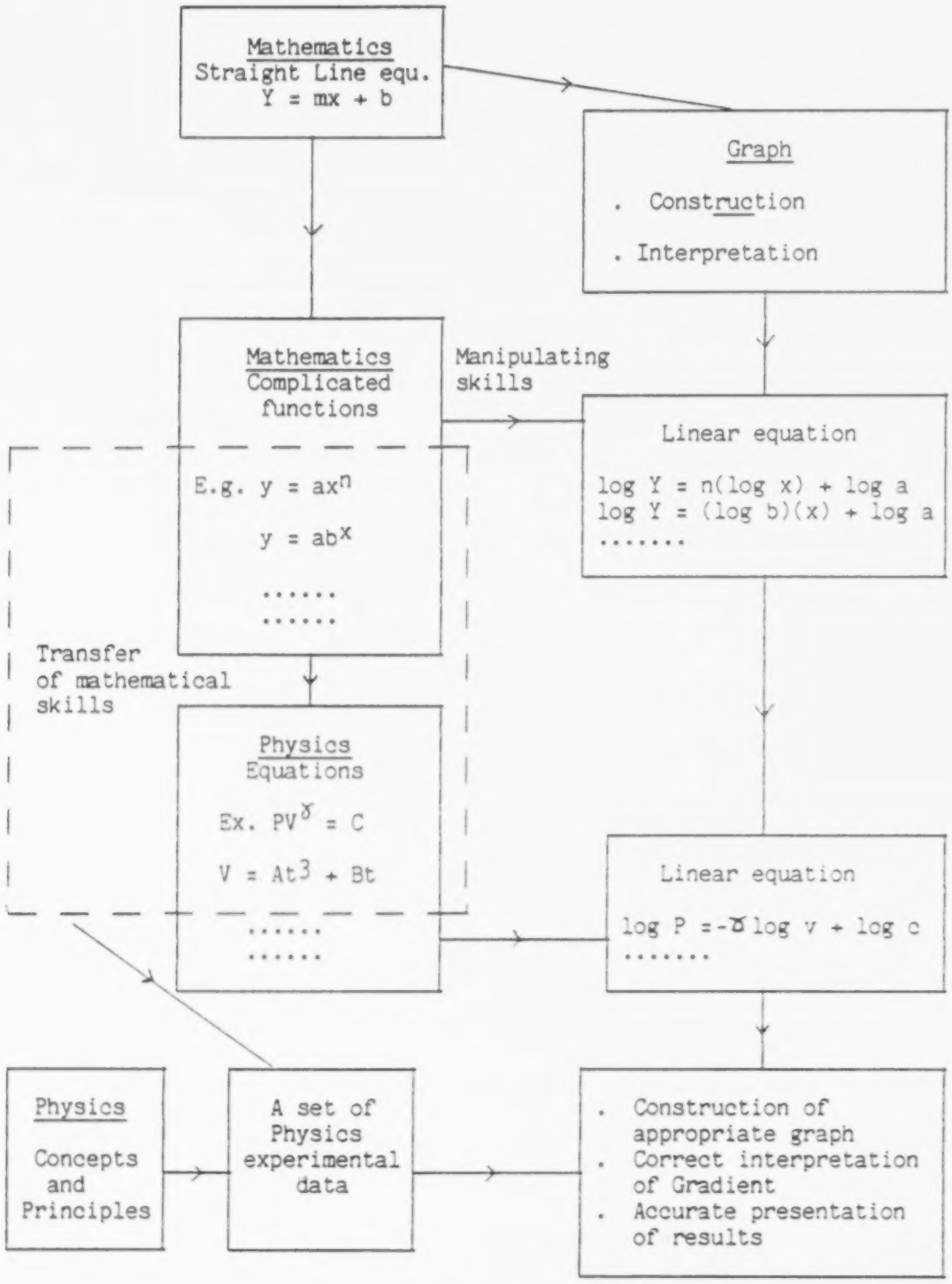

Figure 2. Sequence of the Teaching Unit on Graph

Errors

The common problems faced by students in physics practical are calculating errors and making estimation. Many students have difficulties in making approximations by discarding terms which do not affect the answer as well as in giving the answer in a reasonable number of significant figures. The objectives of this teaching unit include:

- differentiating mathematical expressions
- estimating the maximum error
- using ratios and proportions in calculating percentage errors
- expressing answers in correct significant figure

The skills to be illustrated and stressed are:

- manipulating skill
- transfer skill
- making approximation skill
- interpreting skill
- presenting skill
- skill in making estimation

Figure 3 shows the procedure of how the topic will be presented.

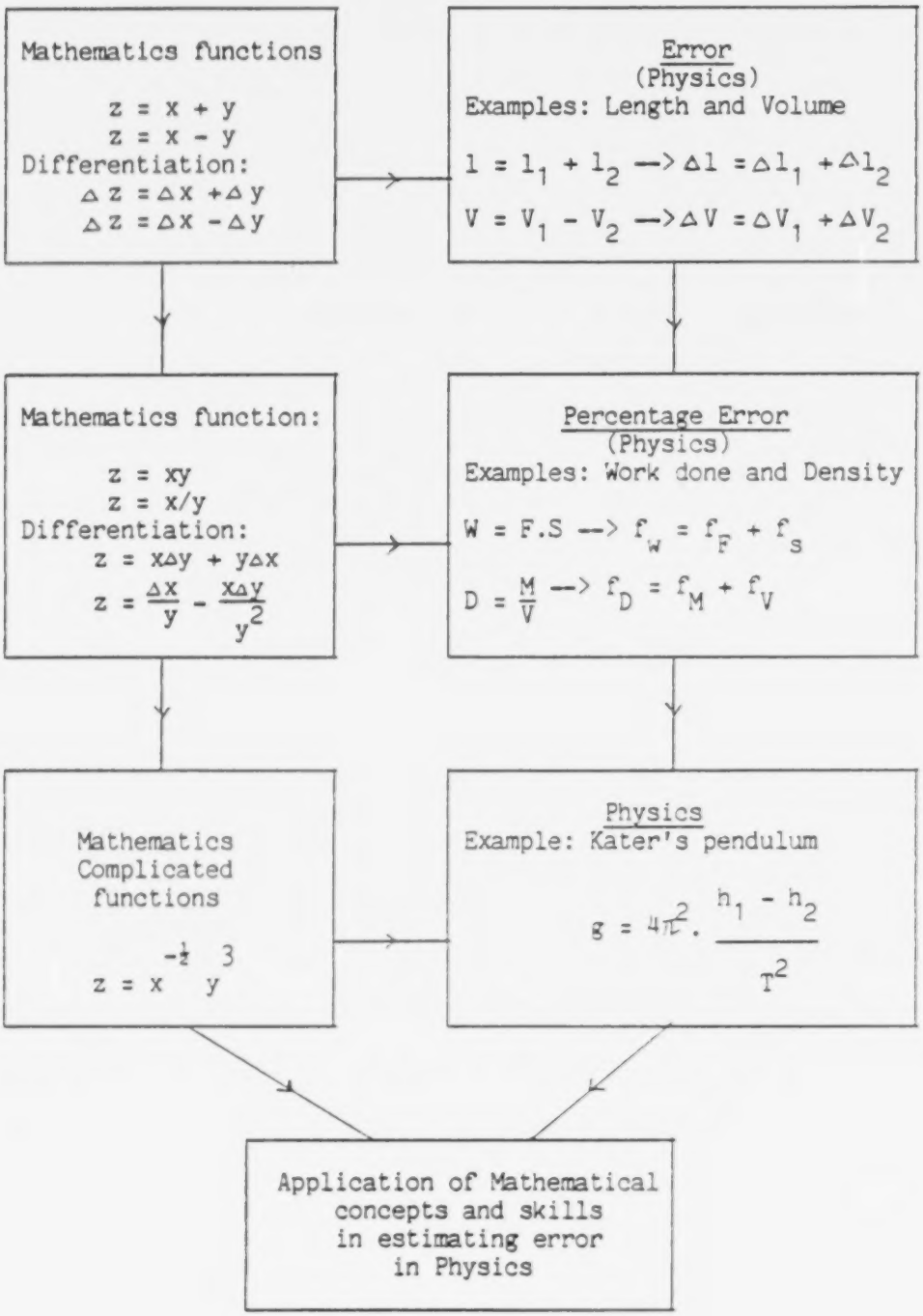

Figure 3. Differentiation in Mathematics and Error Estimation in Physics

Composition of Vectors and Resolution of a Vector

The concepts of vector, composition of vectors and resolution of vector are fundamental concepts in both Physics and Mathematics. The generic ideas of vectors is the foundation stone for many areas in physics and mathematics. A lack of understanding of the nature of vector quantities may restrict students from further understanding of many other physics topics. At the introductory level, pupils do find difficulty in assimilating the properties of vector in the discussion of force, acceleration, velocity and especially relative velocity. Analysis of the difficulties faced by the students indicate that they use the vector notation devoid of physical meaning.

To help students to grasp the notion of vector in mathematics as well as its application in physics, demonstration-observation-explanation teaching method is adopted. Simple but useful apparatus made of transparent perspex are used with an overhead projector to perform demonstrations such as:

- vector addition

  simulation of a river crossing observed by an fixed observer at the river bank.

- vector subtraction

  simulation of a bird flying directly over the river as seen by an observer floating down the river.

- vector resolution

  the equilibrium of three forces.

There are many other demonstrations which can be carried out by using these simple apparatus. The concepts included in the teaching unit are listed in Table 1 and the general network for physics vector quantity is shown in Figure 4.

Table 1

Mathematics concepts	Application in Physics
Notion of Vector - Direction - Magnitude	Physics vector quantities Examples: Force Acceleration Velocity Momentum ....
Vector Addition Methods: - Parallelogram - Triangle - Polygon	- Resultant of forces acting on a body - Resultant velocity-ferryman's problem - Three forces in equilibrium ....
Vector Subtraction Methods: - Parallelogram - Triangle	- Relative velocity and relative acceleration with respect to a moving observer - the direction of rain drop seen by an observer in a moving car .....
Resolution of a Vector - Independent components (components perpendic among each other)	Resolution of Physics vector quantity (force, velocity, etc.) with its components along certain directions according to Physics situation and for the purpose of solving physics problems in an effective way.

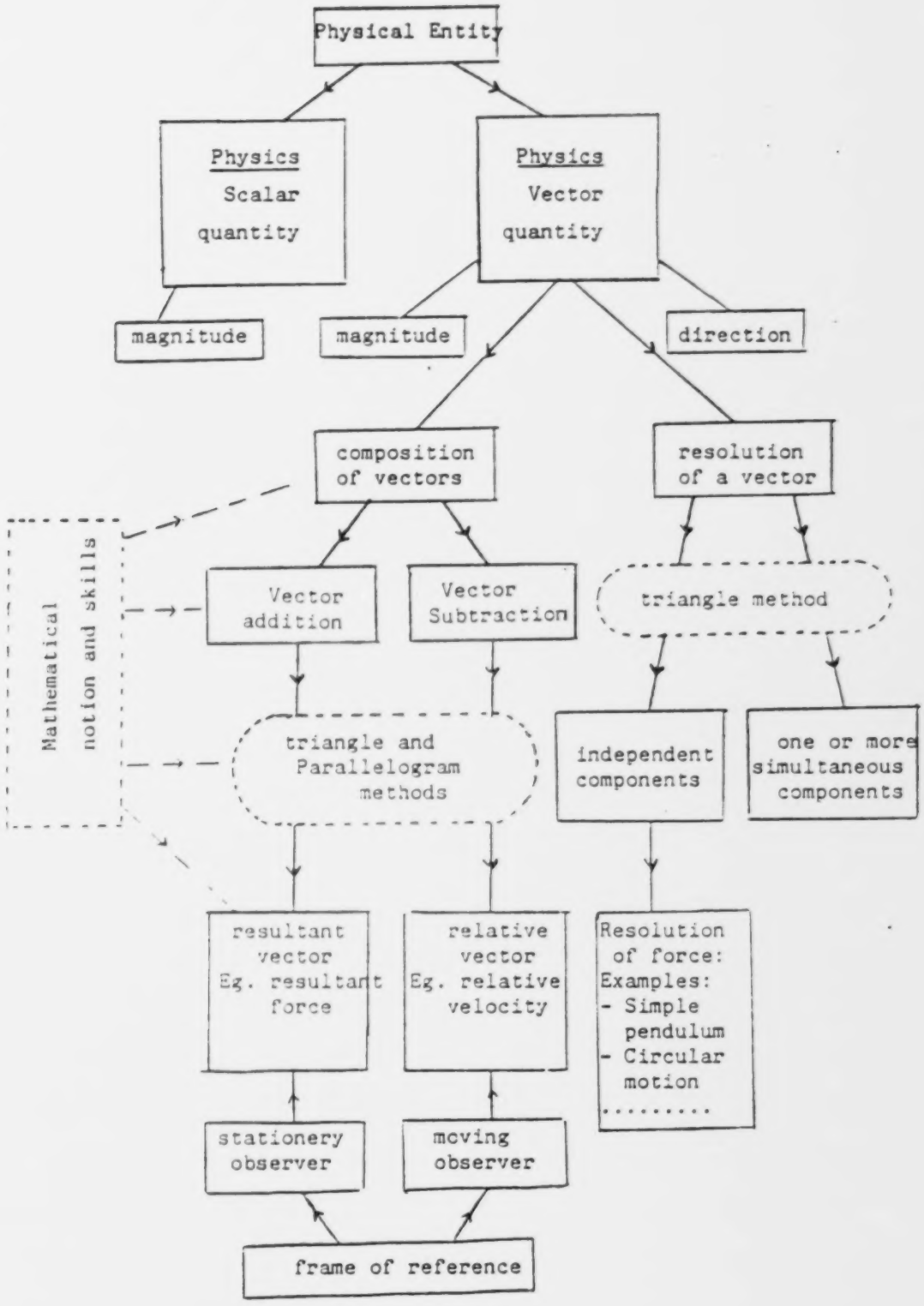

Figure 4 Network for vector concept of force, acceleration, velocity, ...

3.5 Instructional Methods

The instructional methods adopted in this study were combinations of the following methods:

Method	Treatment components
Prototype Development	Definition + Explanation of examples and non-examples
Interrogatory	Definition + Questions related to illustration
Demonstration, Observation and Explanation	Prediction of the outcome of demonstration + demonstration and observation + discussion on the conflicts between predictions and observations or reinforcement on the correct prediction

The teaching method consisted of the components of immediate feedback and corrective teaching. A set of simple questions was designed to treat deficiencies in prerequisite knowledge and skills in mathematics. After the study of a unit, students were asked to solve a series of questions. Many of the questions were set to expose more common weaknesses in the application and transfer of mathematical skills in solving physics tutorial problems. Immediately after students having answered the questions, teacher provided feedback, which gave the correct answers and information clarifying the incorrect responses.

4. IMPLEMENTATION

4.1 In implementing the study, certain constraints have been taken into consideration. The practical requirement is that the study should be carried out with no addition of manpower or special resources as well as without causing any administrative difficulty. With these in mind, a fused curriculum is adopted. In this study, the way of integrating the curricula is to have

the teacher agree in teaching two subject areas, physics and mathematics. It is also important to ensure that the topics selected for the study follow the scheme of work planned by the college.

In the study, the designed instruction constituted the treatment provided to the experimental group. For comparison, the control group was subjected to the conventional instruction, in which tutors discussed the tutorial questions prepared by the college during the tutorial sessions. The duration of the study was about five weeks. Both groups were given the same amount of time to cover the same topics. Same post-tests were conducted to both the experimental group and the control group.

5. RESULTS AND DISCUSSION

To determine the effects of integrating mathematics skills to physics instruction on students achievement in physics, pre-tests and pro-tests were administered to the students in both the control group and experimental group. Analysis of the data collected was done by using t-test as well as pairwise comparation.

5.1 Analysis of Test-Scores Using T-Test

Pre-Tests Results

The means for both experimental and control groups, the standard error of the difference in means and the t-test result are given in Table 2.

Table 2 Pre-Test Results

Experimental Group Mean	Control Group Mean	$S_{\bar{x}_1 - \bar{x}_2}$	t-value	Decision
49.4	55.1	2.25	-2.53	Reject H_o at $\alpha = .05$

From the pre-tests results, we can conclude that there is a difference in the two groups. The

results confirm that the control group is of better ability.

Post-Tests Results

The mean score for the experimental group is 73.4 and that for the control gorup is 67.1. The standard error of the difference in means is 3.53. The t-test result of the post-tests is given in Table 3.

Table 3 Post-Test Results

Experimental Group Mean	Control Group Mean	$S_{\bar{x}_1 - \bar{x}_2}$	t-value	Decision
73.4	67.1	3.53	1.784	Accept H_o at $\alpha = .05$

From the post-tests results, we see that the experimental group has managed to score higher than the control group. The t-test indicates that there is no difference in the two groups at = 0.05; nevertheless, the difference is significant at = 0.10. However, there is a significant difference in the two groups with the control group being better than the experimental group before the treatment. Thus it can be concluded that the teaching units have been successful i.e. by placing more emphasis in Mathematical skills as well as transfer of mathematical skills during physics lessons, students' achievement can be significantly improved.

5.2 Analysis of Test-Scores Using Paired Sample Theory

Since the pre-test and post-test scores of the same student are investigated, analysis can be done by using the theory of paired samples. The confidence limit for the difference between the means of post-and pre-test is given by:

$$\bar{D} \pm t_{(.975,\ n-1)} \times S\{\bar{D}\}$$

With a 95% confidence interval, the confidence limit for the control group as well as the experimental group are given in Table 4.

Table 4 Confidence Interval

Group	$\bar{D}$	$S\{\bar{D}\}$	Confidence Limits (CL)
Experimental	25.6	3.60	18.3 to 32.9
Control	12.1	3.71	4.5 to 19.7

From the values of CLexp and CLcont, one can conclude that better improvement in performance of the experimental group can be due to the instruction designed and the teaching approach adopted.

5.3 Comparations of Proficiency Levels in Mathematical Skills in the Pre- and Post-Tests

Summary of the applications of mathematical skills in solving physics problems in both the pre-and post-tests is shown in the tables below.

Pre-Tests

Skills	Expt. group $\bar{P}_1$	Control group $\bar{P}_2$	$S\{\bar{P}_1-\bar{P}_2\}$	z^*
Manipulation	.455	.729	.1173	-2.336*
Transfer	.364	.486	.1184	-1.030
Interpretation	.485	.703	.1172	-1.860*
Approximation	.182	.216	.0957	-0.355

* $p < 0.05$

Post-Tests

Skills	Expt. group $\bar{P}_1$	Control group $\bar{P}_2$	$S\{\bar{P}_1-\bar{P}_2\}$	z^*
Manipulation	.909	.848	.0786	0.776
Transfer	.667	.541	.1172	1.075
Interpretation	.697	.756	.1065	-0.554
Approximation	.727	.432	.1185	2.489*

From the tables, we see that students who have undergone the specially designed teaching units have shown more awake in applying the four skills than those who did not go through a similar course in which the skills are explicitly taught.

6. SUMMARY

The results obtained strongly support the notion that in the Physics classroom, with an emphasis on Mathematics skills and the transfer of Mathematics skills, students would perform better in solving Physics problem. Whenever possible, Mathematics concepts should be explained before introducing Physics concepts so that students are able to see the link between the two fields. Mathematical manipulation skill is one important area because when solving a physics problem, students would need to rearrange a given equation to suit certain conditions. The transfer of Mathematics skills to the Physics practice is also found to be important in fostering the growth of students' problem-solving skills.

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PRE-TEST (1)

Graphs and Straight Lines

Transform each of the following equations in the form
$Y = mX + c$

1.

Given equation : $y = ax^2 + bx$

New equation :

Vertical Axis :

Horizontal Axis:

Gradient :

Intercept :

2.

Given equation : $\frac{a}{y} = \frac{b}{x} + c$

New equation :

Vertical Axis :

Horizontal Axis:

Gradient :

Intercept :

3.

Given equation : $y = ax^3 + b$

New equation :

Vertical Axis :

Horizontal Axis:

Gradient :

Intercept :

4.

Given equation : $y = \sqrt{x^2 - a}$

New equation :

Vertical Axis :

Horizontal Axis:

Gradient :

Intercept :

5.

Given equation : $y = a^x b^2$

New equation :

Vertical Axis :

Horizontal Axis:

Gradient :

Intercept :

6.

Given equation : $y = pe^{x^2}$

New equation :

Vertical Axis :

Horizontal Axis:

Gradient :

Intercept :

POST-TEST (1)

Graphs and Straight Lines

1. Transform the relation

$$\frac{y^2}{x} = ax + \frac{b}{x}$$

into a linear equation, stating the axes, gradient and intercept. For 1-D motion under constant acceleration, one of the relations is $v^2 = u^2 + 2as$ where the symbols have their usual meanings.

A ball is thrown vertically from ground level. At a certain height, the velocity is measured. This procedure is repeated for a number of times. A set of data is recorded.

u/ms^{-1}	7.0	8.0	10.0	11.0	9.0
v/ms^{-1}	3.0	4.9	7.7	9.0	6.4

By plotting a suitable graph, determine the height at which the final velocity was taken, given that $g = 10\ ms^{-2}$.

2. Transform the given relation

$$yx^n = a$$

into a linear function of the form $Y = mX + c$.

For adiabatic process, $pV^{\gamma} = a$ where a is a constant
p denotes pressure
V is the volume
γ is a characteristic of the gas

A set of data of V and p is given below:

V / m^3	2.5	4.0	5.5	6.5	9.7
p / Pa	2.7	1.4	0.9	0.7	0.4

by means of a suitable graph, determine the value of γ.

PRE-TEST (2)

Errors and Estimation

1. Given that $x = x_o \pm e_x$. $y = y_o \pm e_y$

$a = x + y$

$b = x - y$

$c = xy$

$d = x/y$

Find e_a, e_b, f_c, f_d in terms of e_x, e_y, x_o, and y_o

2. a) Given $m_1 = (5.23 \pm 0.01)$ g

$m_2 = (9.47 \pm 0.01)$ g

How would you represent $m_1 + m_2$?

b) Given $l_1 = (47.10 \pm 0.01)$ cm

$l_2 = (21.70 \pm 0.01)$ cm

What is the maximum uncertainty in $(l_1 - l_2)$?

c) The force in a wire is given by

$F = kx$ where k = force constant

x = extension

Given that $k = (500 \pm 8)$ Nm^{-1} $x = (0.004 \pm 0.001)$ m, what is the fractional error in the calculation of F?

d) The density of an object is given by the relation

$$\rho = \frac{\text{mass}}{\text{volume}} = \frac{m}{v}$$

Given that $m = (700 \pm 1)$ kg, $V = (0.35 \pm 0.01)$ m^3. calculate the maximum uncertainty in the calculated value of the density?

POST-TEST (2)

Errors and Estimation

1. Given $x = a + b$, express e_x in terms of e_a and e_b.

   For 1-D motion under constant acceleration, one of the relations is

   $$v = u + at$$

   where the symbols have their usual meanings.

   A stone is thrown vertically up with a velocity of (40 ± 1) ms^{-1}. It is timed to take (2.0 ± 0.1) s to reach a certain height. Determine the maximum uncertainty in the calculated value of v.

2. Given that $y = abc$, express e_y in terms of a, b, c, e_a, e_b, e_c. The pressure of a column of fluid is given by

   $$p = \rho gh \qquad (\text{take } g = 9.8\ ms^{-2})$$

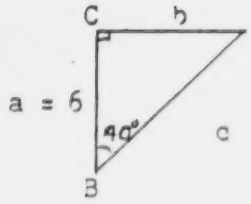
   For a person of height (1.83 ± 0.01) m and given that the density of blood is $(1.06 \pm 0.02) \times 10^3\ kgm^{-3}$, what is the best way to represent his blood pressure.

3. Given that $y = ab^2$, express e_y in terms of e_a, e_b, a and b. The kinetic energy of a particle is given by

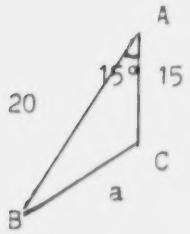
   $$KE = \tfrac{1}{2}mv^2$$

   For a ball of mass (0.133 ± 0.001) kg and moving with velocity (11.6 ± 0.1) ms^{-1}, what is the maximum error in the calculated value of its KE?

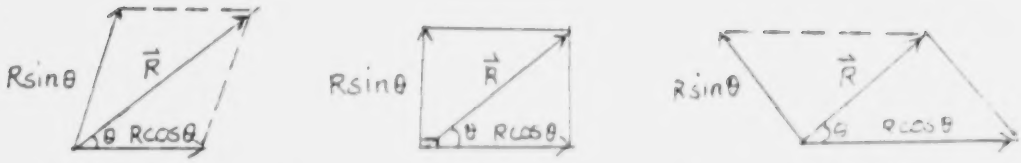
PRE-TEST (3)
Vectors Addition and Subtraction

1. 

Find b, c and A

2. 

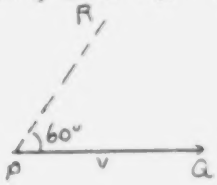
Find a, B and C

3. 

Which of these diagrams correctly represent the resolving of R into its vector components? (Choose the best answer from a, b, c and d.)

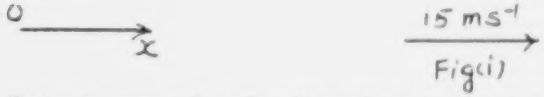
a) diagrams i, ii and iii.
b) diagrams i and ii.
c) diagrams ii and iii.
d) diagrams ii.

4. A particle of mass m moves with a speed v along line PQ. Its momentum in the direction PR is

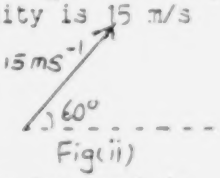


A zero.
B mv/2.
C mv.
D 3mv/2.
E. none of these.

5. A particle has an initial velocity of 15 m/s in the O_x direction, as shown in figure (i). At a later time its velocity is 15 m/s at the angle of 60° to O_x [figure (ii)].



Fig(i)



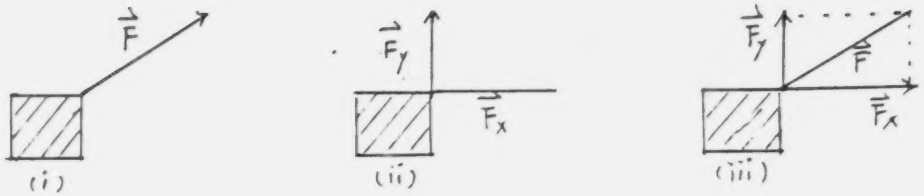
Fig(ii)

The change of velocity that has taken place in this interval is

A zero.
B 26 m/s at an angle of 30° to O_x.
C 15 m/s at an angle of 120° to O_x.
D 25 m/s at an angle of 210° to O_x.
E 15 m/s at an angle of 300° to O_x.

POST-TEST (3)
Vectors Addition and Subtraction

1.



In the diagram above, an arrow drawn represents a force acting on the body. Also, $\vec{F} = \vec{F}_x + \vec{F}_y$.

Which of the diagrams reoresents the same resultant force acting on the body? (Choose the best answer from a, b, c and d.)

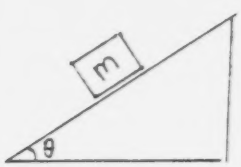
a) i, ii.
b) i, iii.
c) ii, iii.
d) i, ii, iii.

2. A small ball of weight W is suspended by a light thread. When a strong wind blows horizontally, exerting a constant force F on the ball, the thread makes an angle θ to the vertical. Which one of the following expressions correctly defines ?

A $\cos\theta = F/W$.
B $\tan\theta = F/W$.
C $\sin\theta = F/W$.
D $\cos\theta = W/F$.
E $\tan\theta = W/F$.

3. A block of mass m moves down along an inclined plane. Assuming frictionless contacts, choose answers from

A $g \sin\theta$
B $g \cos\theta$
C $g \sin\theta \cos\theta$
D $g (1 - \cos^2\theta)$
E 0



a) its acceleration along the plane is _____.
b) its acceleration normal to the plane is_____.
c) its vertical acceleration is_____.
d) its horizontal acceleration is_____.